Stability, Training, and Protection in High Current Density Windings*

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Superconducting Magnet Program

Acknowledgments

The data and a majority of the ideas and concepts are the work of or done with, or derived from discussions with colleagues in the research groups of which I am a member. The groups are: Lawrence Berkeley National Lab AFRD Superconducting Magnet Group S. Bartlett, B. Benjegerdes, P. Bish, D. Byford, S. Caspi, L. Chiesa, K. Chow, M. Coccoli, S. Dardin, D. Dell'Orco, D. Dietderich, P. Ferracin, S. Gourlay, M. Goli, R Gupta, R. Hafalia, R. Hannaford, W. Harnden, H. Higley, A. Jackson, T. Jaffrey, A. Lietzke, N. Liggins, S. Mattafirri, G. Millos, L. Morrison, M. Morrison, M. Nyman, R. Oort, E. Palmerston, J. Remenarich, G. Sabbi, R. Scanlan, J. Smithwick, J. Swanson, C. Taylor, J. van Oort

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The stability estimate development is given in detail in Dr. M. Wilson's Book "Superconducting Magnets" Chapters 5 through 7. Some particular equations and relationships were first given in BNL 51412 "Stability of Superconducting ISABELLE Dipole Magnets by Stefan Wipf April 1981

- Maximum Compaction w/o degradation

- No Void Space, no epoxy volumes unfilled with fiber glass

- Winding's Desirable Properties
  - Monolithic winding pack
  - No bonding to support surfaces with a shear force (or release)
  - Pre-exercise to obtain the best modulus (load & unload)

- Boundary Value Currents

- Cross strand Resistance
    - non-cored
    - cored

- Highest Compaction w/o degradation

- Minimize Epoxy space with glass and surfaces with mica or release agent

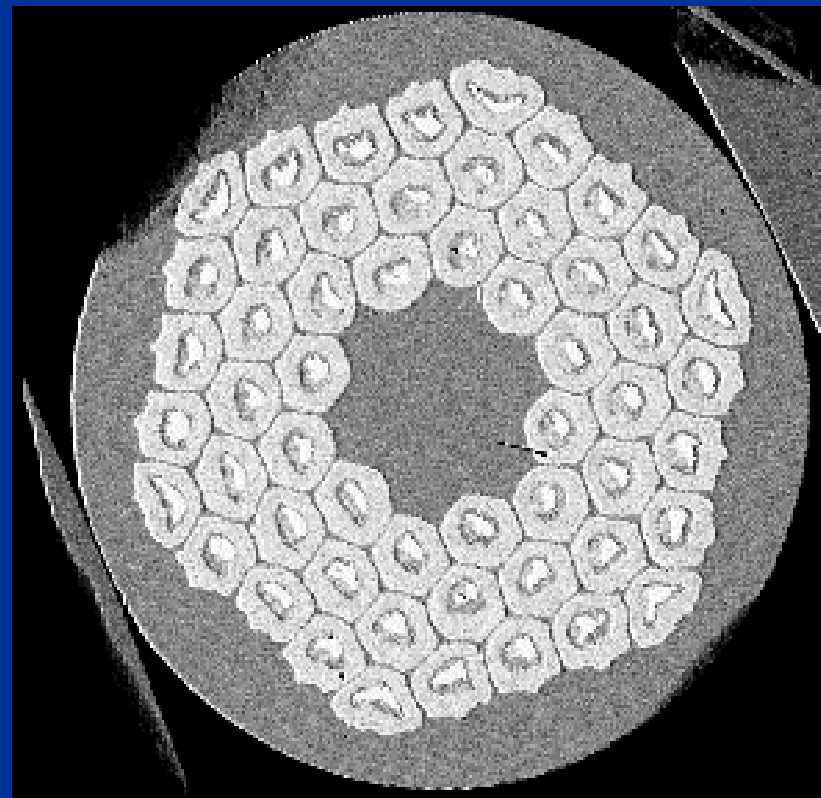- Minimize Insulation film minimum thickness
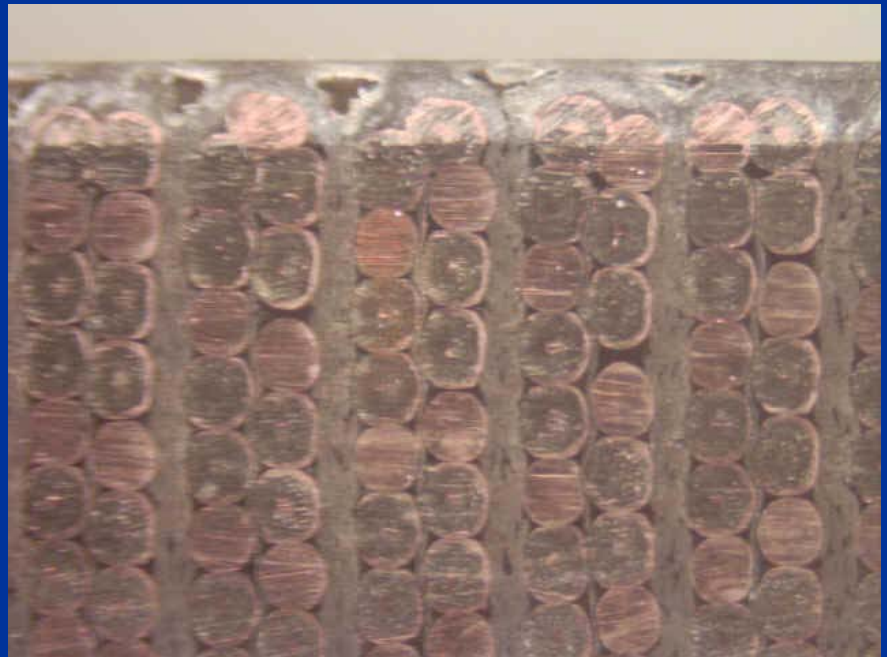
Windings, Cables, Strands, and sub-elements

Strand Stability Estimate Calculations

> Self Field $B_o = \mu_o I_t / 2\Pi a$ ~0.46T

> Diffusivity

- $D_\Theta = K / C_v$

- $D_m = \rho / \mu_o$

> Time Constants of Composite

- Surface heat transfer ~5.2×10^{-3}s

- Magnetic Flux   ~5.1×10^{-3}s

- Internal heat transfer ~1.7×10^{-3}s

Composite & Sub-Element Stability Estimate
Calculations

"Dynamic Stability Calculations"

$$a < 8^{1/2}d$$

$$d^2 = K(\theta_c - \theta_o)(1 - \lambda)/\lambda J^2 \rho$$

$$d \sim 41 \mu m$$

$$a = 116 \mu m$$

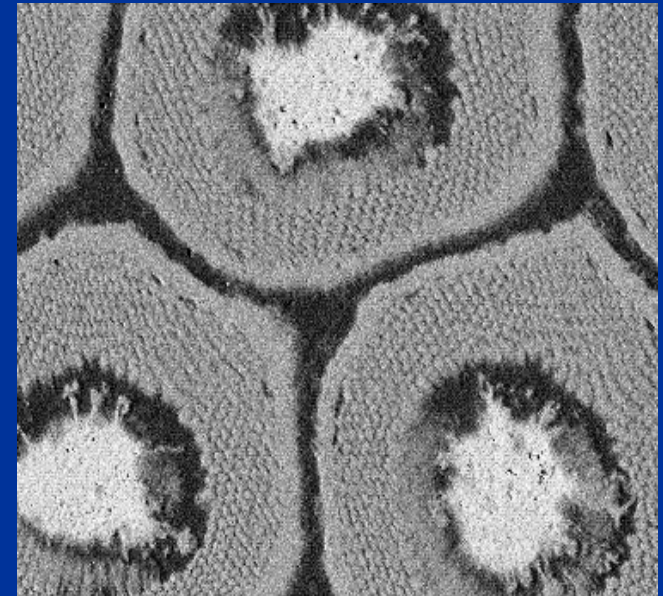Using HD1 as an example physically $\sim 70 \mu m$
for the sub-element at 12T

$$B_o \sim 0.08T$$

The Flux Jump Field B_{FJ}

$$B_{FJ} = (2\mu_o C_v J_c/(-dJ_c/dt))^{1/2}$$

$$B_{FJ} \sim 0.16T$$

Sub-Element Stability Estimate Calculations

> Surface Shell (Nb_3Sn)

- $h = K/w = 5 \times 10^{-2}$ w/mK/16μm

$\sim 3.1 \times 10^3$ w/m²K
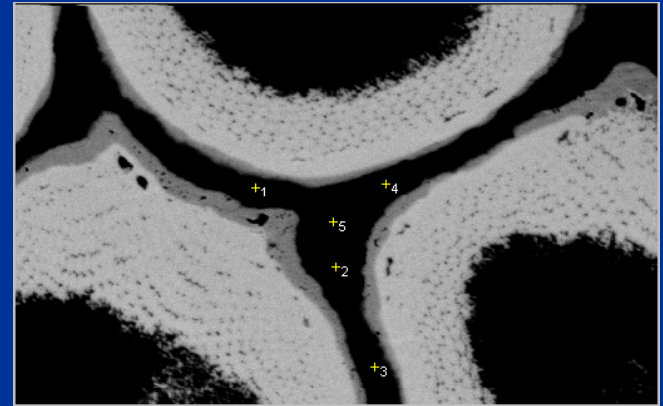
$\tau_\theta = C_v a/h = 206$ s

> If 10% of sub-element shell were bronze fins:

- "τ_θ" would decrease $\sim 10^3$

- aids de-coupling magnetically as well

D_θ(Cu7.5w/oSn) = 7×10^{-2}m²/s

$D_m = 8 \times 10^{-2}$m²/s

Position 1

Elmt	Spect. Type	Element %	Atomic %
Cu K	ED	270.19	97.94
Nb L	ED	5.79	1.44
Sn L	ED	3.21	0.62
Total		279.19	100.00

Position 2

Elmt	Spect. Type	Element %	Atomic %
Cu K	ED	277.41	99.45
Nb L	ED	0.49*	0.12*
Sn L	ED	2.25	0.43
Total		280.15	100.00

* = <2 Sigma

Position 3

Elmt	Spect. Type	Element %	Atomic %
Cu K	ED	264.84	96.64
Nb L	ED	11.82	2.95
Sn L	ED	2.09	0.41
Total		278.75	100.00

> If the FJ reduces the composites effective "ρ"

  D_m would be smaller by 10 (Yasukochi '81)

> Another more conservative approach would

  suggest: if "B_p" were 0.16T then

    - $\mu_o J_c a_{eff} = 0.16T$ or $a_{eff} = 16\mu m$

    - ~32μm diameter filaments

> This appears to be possible in the near future!

> However present operations appear to have
. Exceeded % short sample predicted by   .
. Stability parameter "β_t "

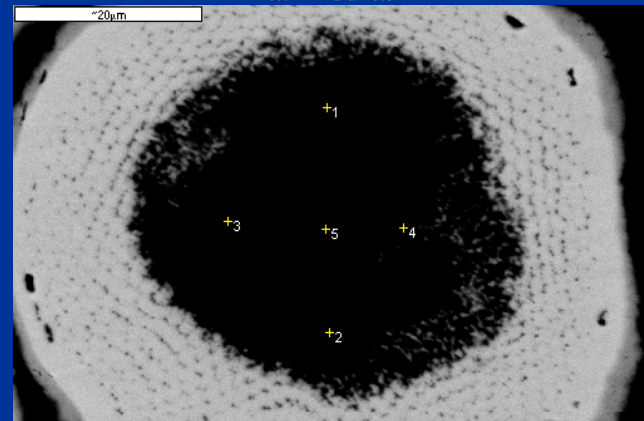$$\beta_t = \mu_o \lambda^2 J_c^2 a^2 / C_v(\theta_c - \theta_o)$$

Manufacturers More J_c Please!

6555 Cu-Sn Compositional Analysis
100 hours at 210 °C
48 hours at 340 °C
100 hours at 650 °C
0.7 mm diameter

~20μm

Position 1

Elmt	Spect. Type	Element %	Atomic %
Cu K	ED	256.37	95.59
Nb L	ED	0.45*	0.11*
Sn L	ED	21.54	4.30
Total		278.36	100.00

* = <2 Sigma

Position 2

Elmt	Spect. Type	Element %	Atomic %
Cu K	ED	251.66	95.06
Nb L	ED	2.23	0.58
Sn L	ED	21.60	4.37
Total		275.49	100.00

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Training Cos Θ coil - D20

- $J_{non\ cu}(12T, 4.2K) \sim 735A/mm^2$

- Preload<Lorentz load
  ~100MPa vrs 140MPa cal. Lorentz

- Pole/1st turn Separation
  >pole turns account for 42% of quenches and 23 of 1st 25

- **Soft Support** for a bottom outer coil lead which is the source of 33% quenches

D20 INSTRUMENTATION LOCATION
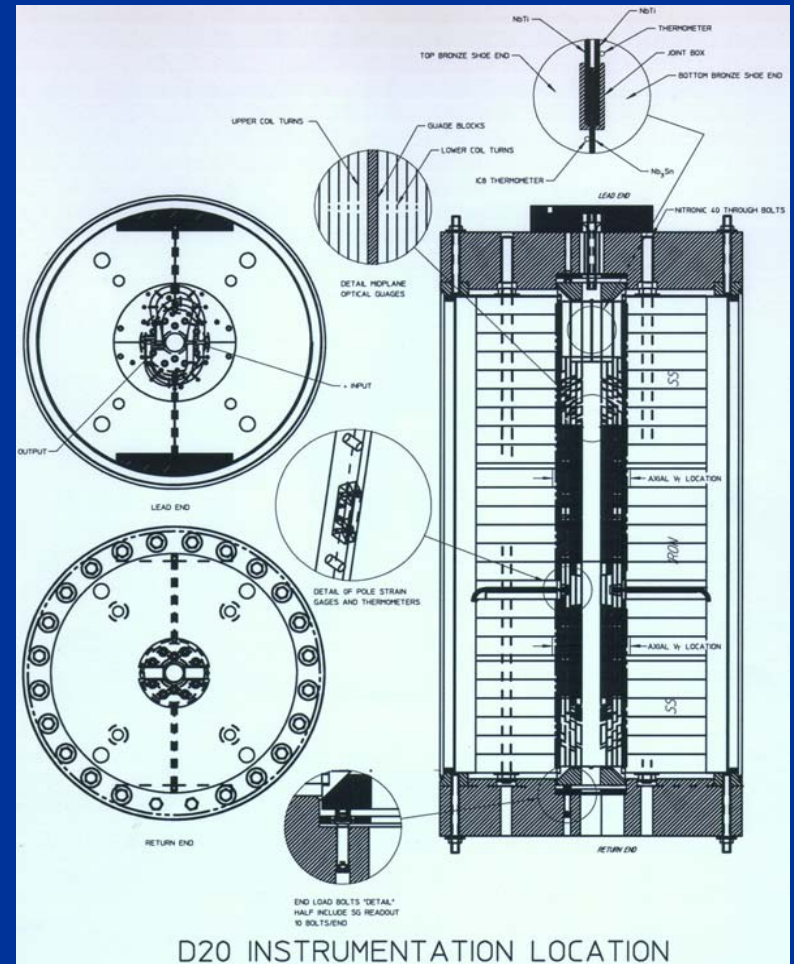
Training Cos Θ coil - D20

- **Protection Heaters** adequate
  peak quench spot temperature
  <235K

- **Windings very Rugged** >100
  quenches driven and natural no
  apparent problems

- **Low End Loads** less than 5%
  of calculated load measured at end

- Record Dipole Fields 12.8T
  , 4.2K and 13.5T , 1.9K
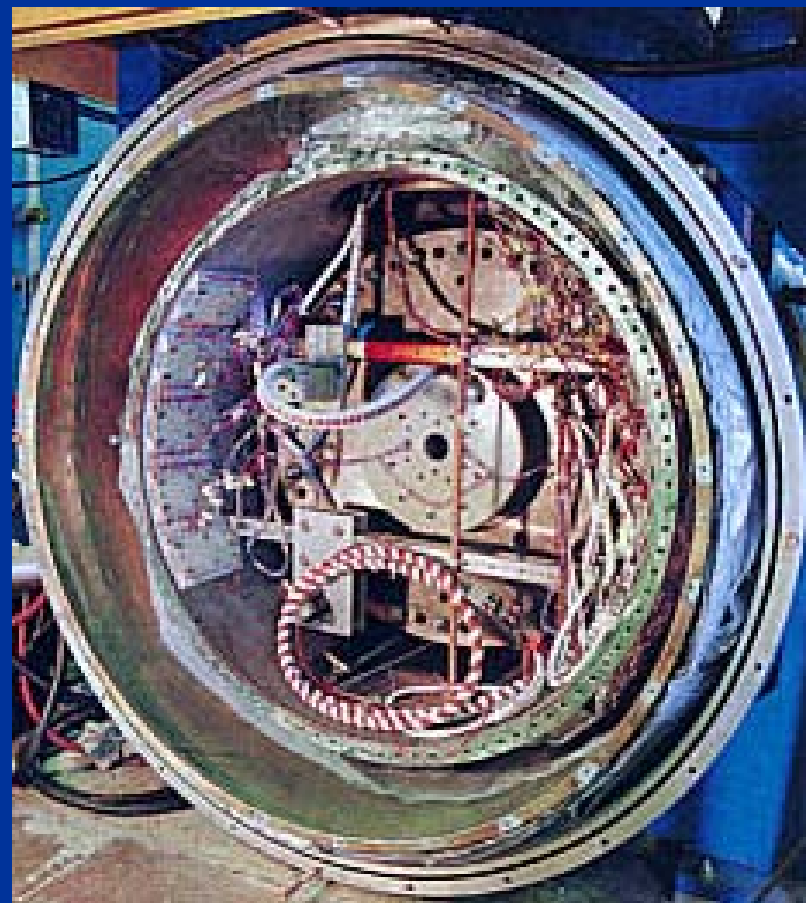
Training Cos Θ coil - D20

D20: Training History

Superconducting Magnet Program
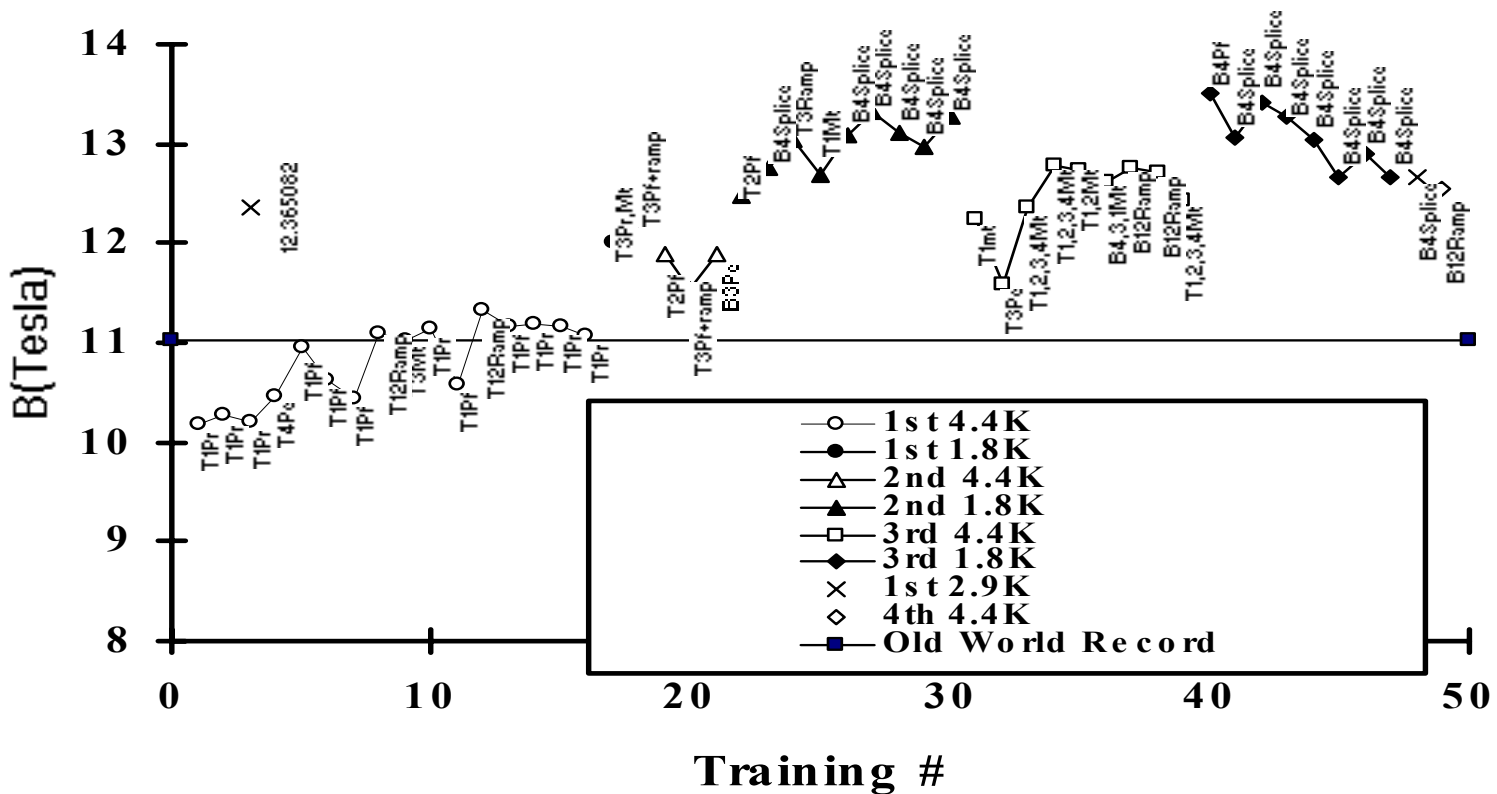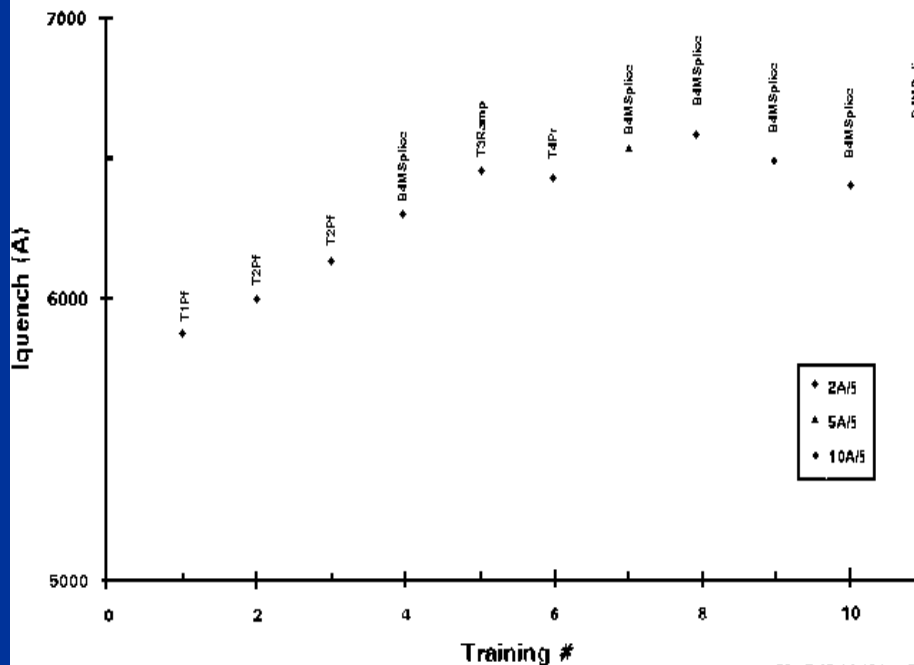
Training Cos Θ coil - D20

D20:"1.8K" Training History

Super Fluid Quenches

- Training still at Super Fluid peak field 13.5T vrs ~13.8T SS

- S.F.T. shortened the 4K training , but did not eliminate it

- Problem with the outer coil lead stability first appears at super fluid temperatures!

Training Cos Θ coil - D20

- After fourth cool down, the magnet ran reliably at 12.5T (12.8T measured short sample)

- The coil had a 20w margin at 12.5T 4.5K

- Summary: There were two clear problems:
  - Bonding to post &/or low pre-load
  - Excess soft insulation leading to conductor motion

- These account for 75% of the 60 training Quenches

Apparently Stable!

D20: Recent Training History

Legend:
- 3rd 1.8K
- 1st 2.9K
- 4th 4.4K
- 2nd Cooldown
- 5th Run - KEK
- Old World Record

X-axis: Training #
Y-axis: B(Tesla)
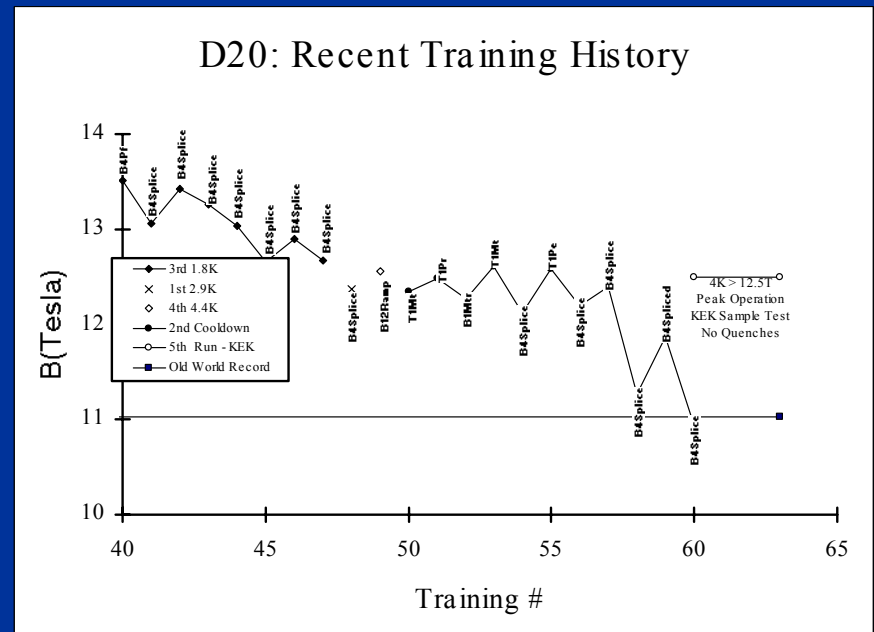
- First Av. "J" Common Coil

> Pre-loads varied over large range

> Peak Field ~6T

> Loads varied over many
. . Configurations

* No Training Observed!

Magnet configuration	Load at 300K Horizontal	300K Vertical	4K Horizontal	4K Vertical
RD-2-01	30 MPa	30 MPa	50 MPa	30 MPa
RD-2-02	6 MPa	6 MPa	50 MPa	30 MPa
RD-2-03	6 Mpa	6 Mpa	21 Mpa	12 MPa
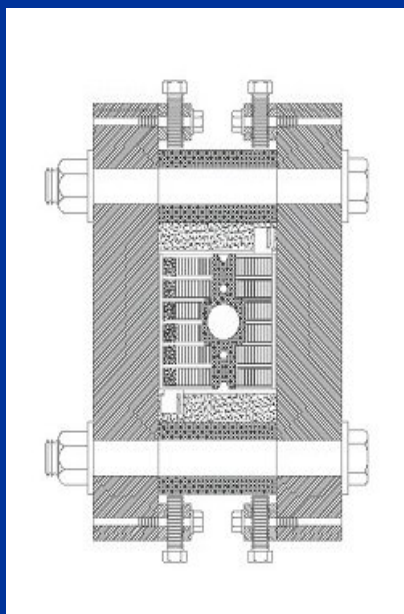
RD2- Series Assembly
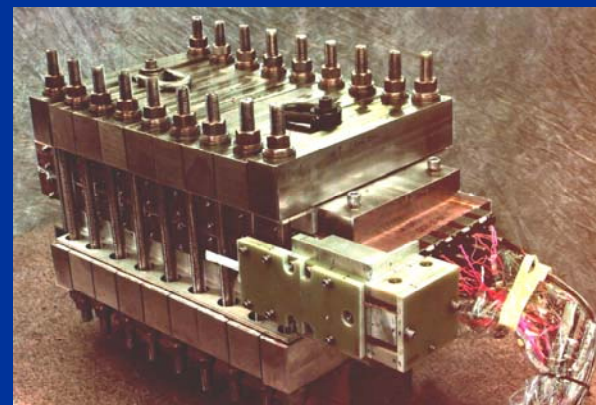
14 Tesla Common Coil Design

- **Main coil spacing**   25 mm
- **Quench field at 4.2 K**   14.4 T
- **Quench Current**   10.8 kA
- **Number of layers/mod.**   2
- **Coil modules**   3
- **Straight section length**   500 mm
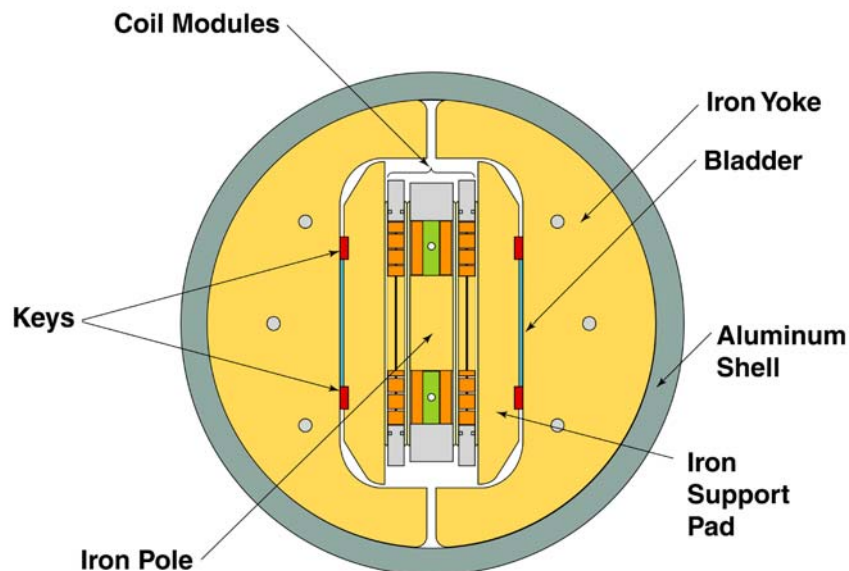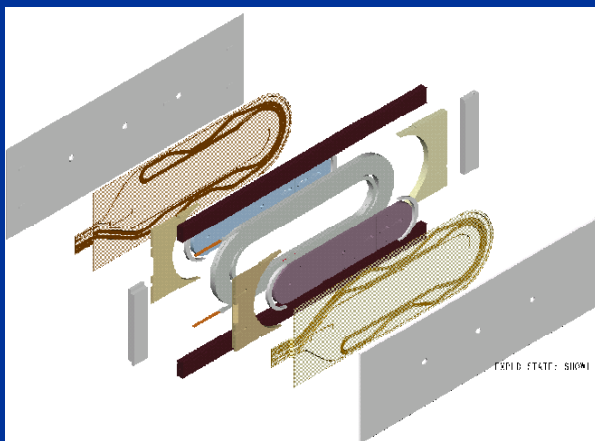
- ## Outer Module's Configuration
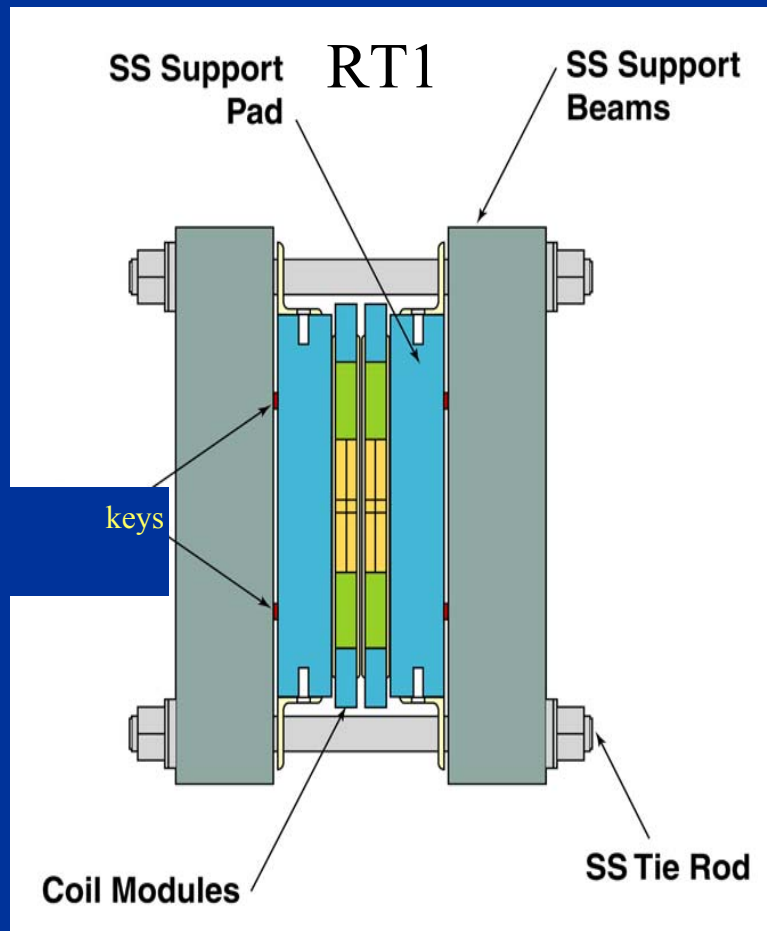
Coil Module Loading and cycling

RT1

SS Support Pad

SS Support Beams

keys

Coil Modules

SS Tie Rod

2/3/2000

> Modules preloaded repeatedly

> Weld shrinkage increased load

Training Common Coil RT1

- RD3 Module Pretesting alias RT1

- High Fields (12T) no gap between

- Large Forces between Modules ~6.9 MN or 775 tons

- Large Module separation ~1.8mm

- 3 Training Quenches 96%, 93%, and 98% of short sample

RT1 preloaded in Support

1.5 inch SS tie rods

4.5 inch thick SS structural beams
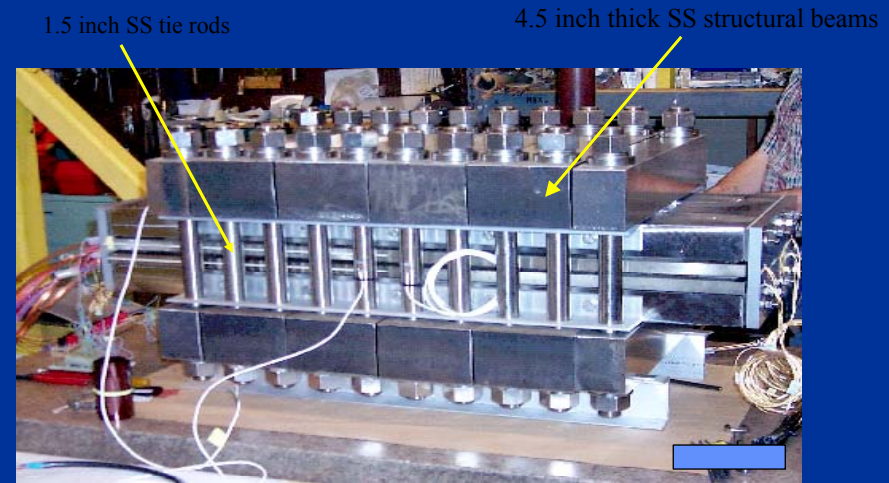
Training Common Coil RD-3

Features

- Large Force 3×10^6 lbs horizontal

- Conductor Stress >100 MPa

Performance

- Previously quenched & virgin outer modules displayed similar behavior

- Both outer modules began quenching at a lower Lorentz load than the trained one before (> 13.7 T)

- First time the inner surface of the outer modules were loaded!

- The inner and 2 outer modules had nearly identical short sample limits.

RD3b awaits Test

Training Common Coil RD-3

- Quench history slope changes when the quench origin switched from inside to outside.

- Moderate improvement of "I_q" after a full thermal cycle (a.k.a. D20).

- RD3c (different middle module with larger aperture) had all but 2 quenches in the already tested outer modules.

- RT1 was the only configuration of this series that had a great training history

RD3-B
Hall Prob measured field

■ ■ after RT cycle

B (T) vs Quench #
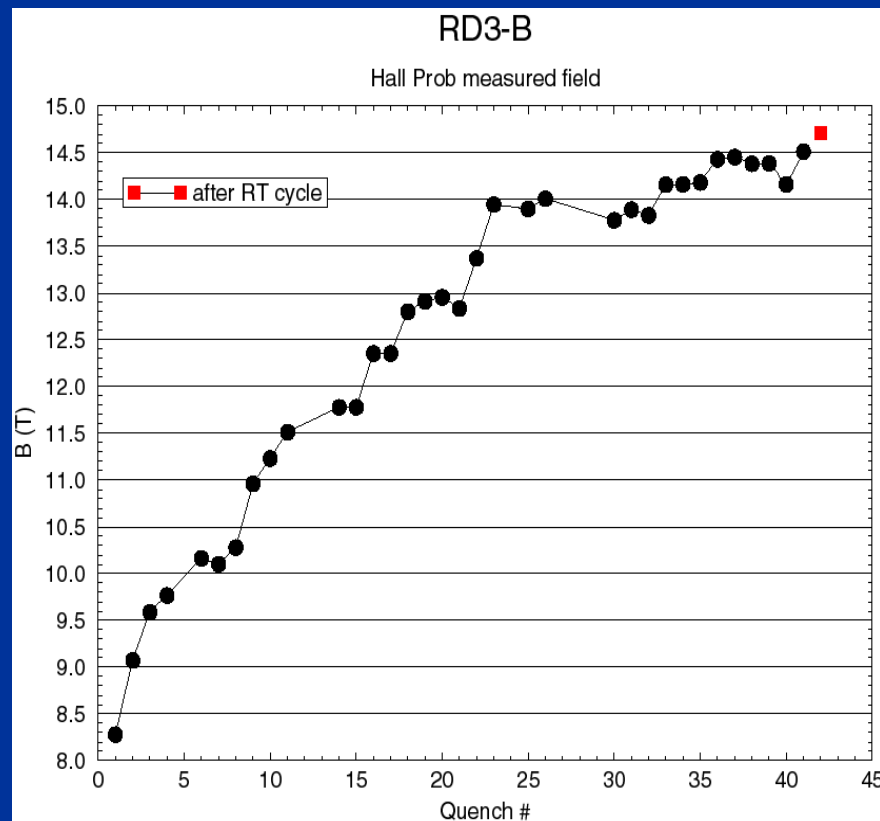
Training Sub-scale Model Program

Technology development and increased productivity with a parallel test program

- Scaled version of full-size magnet
  - Approx. 1/3 scale

- Field range of 9 – 12 Tesla

- Simple two-layer racetrack coils
  - 5 kg of material per coil

- Streamlined test facility
  - Small dewar (no refrigerator)

Sub-Scale Model Magnet Series

- First sub-scale magnet (SM01a) was to have the equivalent geometry as RT1

- First version "SM01a" had a nominal load of 13,000 psi

- Second version "SM01b" had a minimum load of 1,500 psi

- The second coil module "SC02" 's skins were not welded although pre-stressing cycles were done

Training -Normalized Quench History

Summation of all coil's Performance Normalized

- Poorest Peak Performance RD3c & SM01a (both candidates for S.F. training)

- RD3b displayed the poorest training history

- Best Performance was RT1 & SM01b
  - Both had <50% Lorentz load
  - Both had one face loaded the other face not
  - Both had experienced large deflections under field

Training History

I(quench)/I(short Sample) vs Quench Number

Legend:
- D20
- RT1
- RD3b
- SM-01a
- SM-01b
- Rd3c
- HD-1
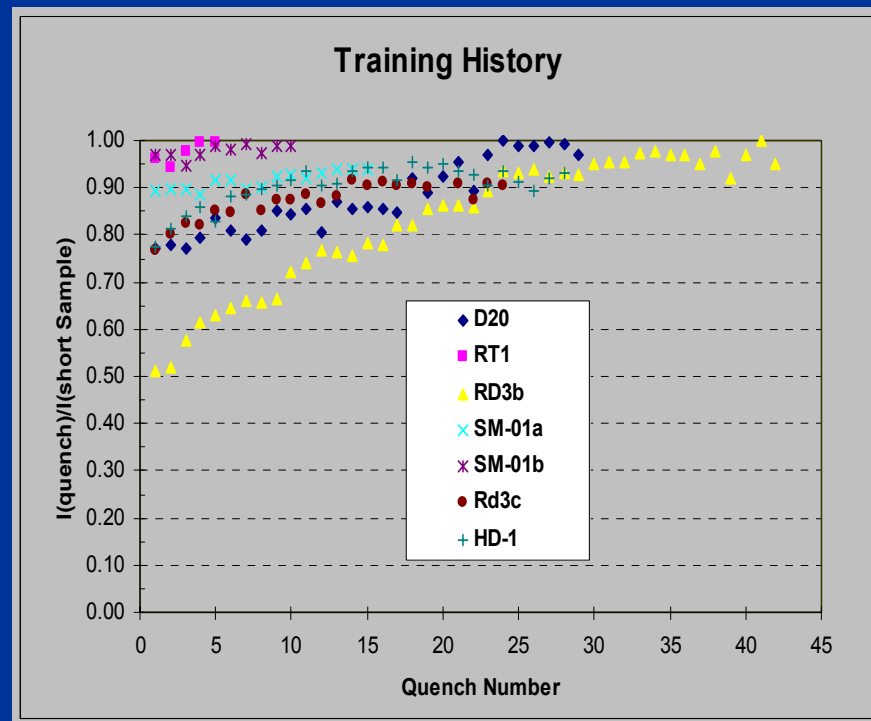
Note for clarity RD-2-01, RD-2-02, and RD-203 are not plotted they would be at 1.0 for the 1st quenches.

Training

MAGNET	D20	RT1	RD3b	RD3c	SM01	HD1
Jc (A/mm²) (12T, 4.2K)	960, 1600	-	2043	2014	-	-
	1627	2143	2143, 1754	2143, 1754	2260	3000
Jcu (A/mm²) (12T, 4.2K)	2240, 1481	-	2270	2319	-	-
	1535	1367	1367, 1329	1367, 1329	2774	1400
No. strands	37	-	40	31	-	-
	47	26	26	26	20	36
No. turns	16+26	-	50	16	-	35
	40+56	49	49	49	20	35
Cu/SC	0.43, 1.08	-	0.90	0.90	-	0.72
	1.06	1.64	1.64, 1.35	1.64, 1.35	0.81	0.96
Strand diam. (mm)		0.753	-	0.800	0.800	-
	0.482	0.800	0.800	0.800	0.710	0.8
Thickness (mm)		1.356	-	1.386	1.396	-
	0.873	1.408	1.408	1.408	1.270	1.546
Width (mm)	14.45	-	17.20	13.32	-	-
	11.63	11.34	11.34	11.34	7.80	16.01
Pitch length (mm)		93.50	-	119.80	93.40	-
	81.28	81.28	81.28	81.28	54.88	81.28

* Cable values are an average of the known strand values.

** When two rows exist, the upper row is associated with the inner module.
   (if it existed) Lower row outer module

*** The second of two values separated by comma refers to an identical coil
   with a different conductor

Standard Age olde Wisdom

- Hold Winding package under compression in all dimensions that is greater than the Lorentz Load plus a safety factor. I.e. do not leave any place for the winding to go.
  - Problem This may be very difficult to obtain in multipole magnets
    - and/or
    - Alternate Strategy and/or Scheme

- Remove the bond between the windings and support surfaces that are not supporting the Lorentz Load (particularly separating ones)

- Moderately load the winding enough to remove the fluff. I.e. < MPa and that the windings are in contact with the Lorentz force bearing surface

- Allow the coil to move as much as the desired field quality will permit and it is in contact with the supporting surface from the start of energizing.

- Low RRR is not a problem if fairly uniform and $\geq$ 10. I.e. both stability and protection are aided by the bronze's presence.

- Filament sizes in excess of a 100 μm for "MJR" or "RRP" process are on the edge of stability and therefore caution is in order

Training Block coil - TAMU-4
"Stress managed"

Training Improvements Attempted

- Two Surfaces not bonded & possibly a third

- Moderate loads on winding (spring only)
  During heat treatment and before powering
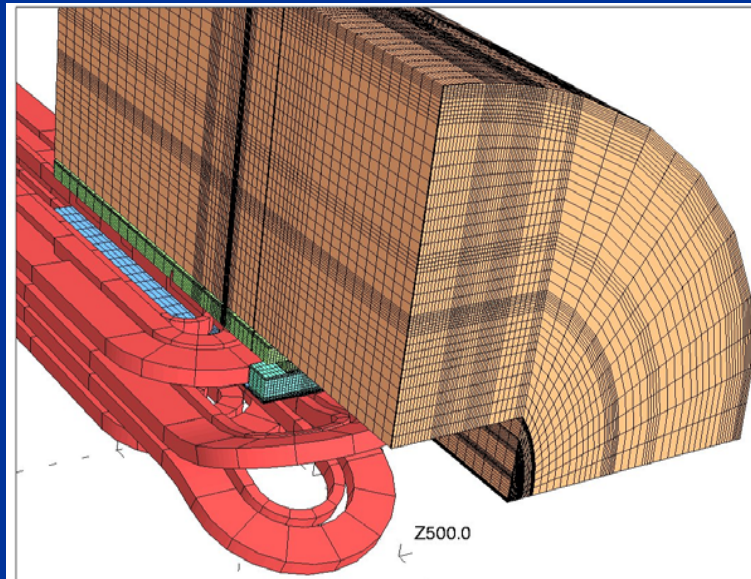
Cross Section of a coil quadrant

Green bars in front of turns are springs
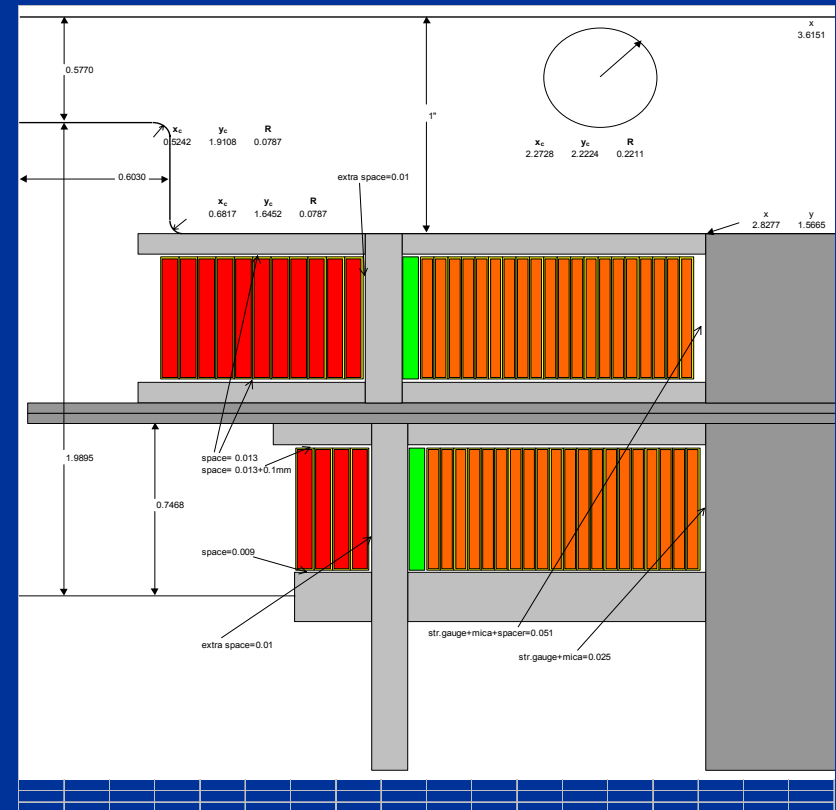
HD1 is the present generation LBNL high field dipole magnet winding being investigated for it's potential. HD1's main objective is field not training performance, but it certainly has been recorded. To date the magnet has achieved a maximum bore field of 15.97 $\pm$0.049T at 4.4K
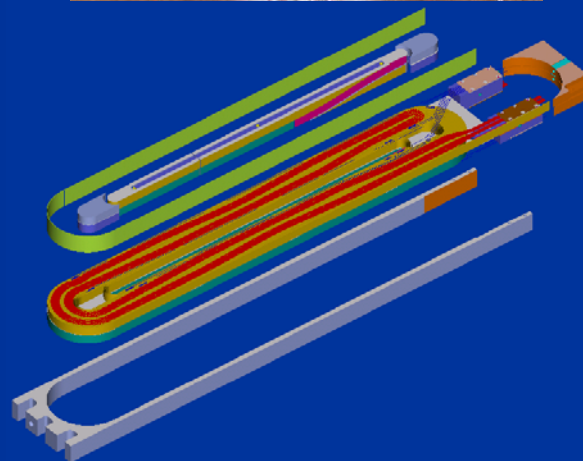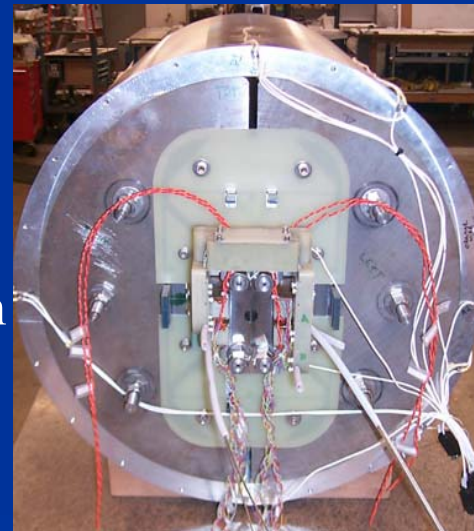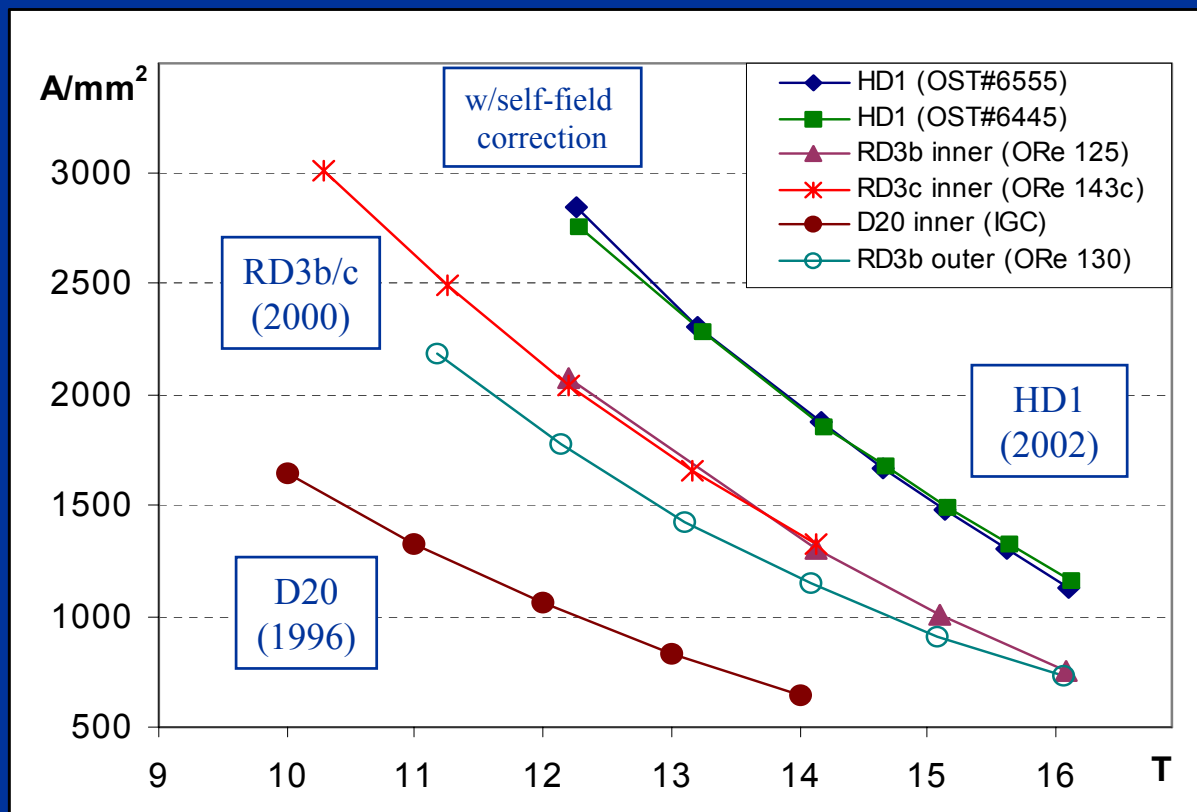
HD1 Conductor

HD1 Conductor
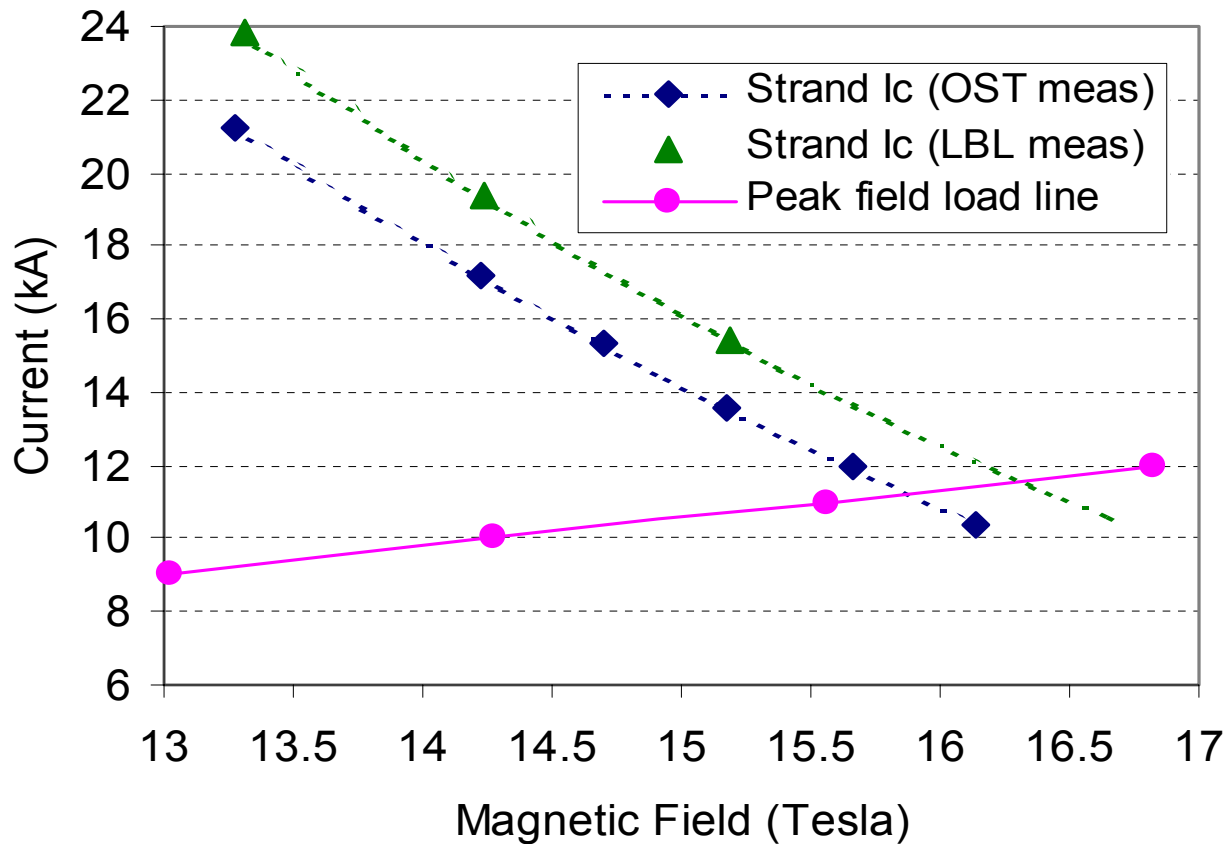
Conditions Assumed in Talk

- Protection to be accomplished by a close proximity heater

- Highly efficient coil winding package $J_{eff} > 1000$ A/mm^2

  currently: $J_{eff} \sim$ 1500 - 2000 A/mm^2

- Examples given will be limited to Nb$_3$Sn coils. "Should be applicable to other A-15's"

- Heater constructed composites of Kapton/SS(cu)/ Kapton plus glue

Definitions

Conductor MIIT's	$\equiv$	10^6 Amp^2 -sec to reach 450K
		a) measured
		b) adiabatic calculation

Critical ramp rate $\equiv$ Rate of current change at which the conductor's temperature rise exceeds it's critical temperature at ~0.9Ic

Minimum ProtectionWinding volume(conductor length) transitioning $\equiv$ That length of conductor which will result in a L/R time constant period that will stay within the conductor MIIT's budget

RRR $\equiv$ Resistance Ratio of the conductor between room temperature & T_{c2}^+

Typical Design of a Heater for a Nb$_3$Sn Race Track Coil

For example HD-1

Conductor Parameters:
   36 strand cable
   0.8 mm strand diameter
   J_c(non-cu, 12T, 4.3K) = 3000 amps/mm^2

Typical design input:
   Quench output page

Typical MIITs Curve:(RD-3 shown)
   Quench's MIIT's Curve for HD-1 is 19 Miits instead of 12.4

First order heater considerations HD-1:
   Inductance = 7mh
   L/R = ?   at 11.2kA/turn yields 125 MIIT's/second

   MIIT's limit "Quench" =19.2 - Room Temperature
   => 157 milliseconds
   -   40   "   detection & diffusion
       117   "

   =>0.235 seconds = t(effective)
   R = 0.007/0.235 ~ 0.034 ohms

HD-1 coil's room temperature resistance = 0.460 ohms

20K R(expected) = 0.02 ohms

20K R(measured)= 0.031 "   note the dramatic "RRR" effect

=> ¼ of the coil driven normal will work

Typical Design of a Heater for a Nb$_3$Sn Race Track Coil(continued)

=>0.235 seconds = t(effective)

For example HD-1 continued

R = 0.007/0.235 ~ 0.031 ohms

HD-1 coil's room temperature resistance = 0.460 ohms

20K R(measured)= 0.0321 ohms

Now a look at the possibility of a quench back!

Assume 1/2 of the magnet is driven normal at ~40 milliseconds

Then L/R = 0.007/0.016 ~ 0.11 sec

or dI/dt = -25,600 amperes/sec. ->96,000 amperes/sec.

The slowest rate is 100 greater than that required to quench HD-1 at 25% of it's plateau current!

$\equiv$ **Quench Back**   will occur <30milliseconds

Protection of D20

A very conservative approach was taken:

      70% of the magnet volume was under heaters

      The power level was set for Super Fluid operation

            Layer 1 = 53 watts/cm^2

            Layer 2 = 23 "

            Layer 3 = 29 "

            Layer 4 = 27 "

The highest average temperature Quench was: outer turn = 165K - 185K

                          inner turn = 80K - 120K

The MIIT's curve predicted: outer turn = 234K ; inner turn = 152K

"Quench" Code Input/Output for MIITs

```
COMPONENT PROPERTIES
  FRAC     THETA     A       AEX      B        BEX       C       CEX       D        DEX       RMAG
  .4090      .00   .4250E-07  .0000  .1670E-11  2.6900  .8000E-05  3.0000  .0000E+00   .0000    1.0000
  .4090    40.00   .4250E-07  .0000  .1670E-11  2.6900  .2300E-02  1.5000  .0000E+00   .0000    1.0000
  .4090   100.00   .1380E-08  1.2300 .0000E+00   .0000  .3000E+01   .0000  .1200E-02  1.0000    1.0000
  .0710      .00   .1700E-05  .1200  .1670E-11  2.6900  .8000E-05  3.0000  .0000E+00   .0000    1.0000
  .0710    40.00   .1700E-05  .1200  .1670E-11  2.6900  .2300E-02  1.5000  .0000E+00   .0000    1.0000
  .0710   100.00   .1700E-05  .1200  .0000E+00   .0000  .3000E+01   .0000  .1200E-02  1.0000    1.0000
  .2120      .00   .1000E+11  .0000  .0000E+00   .0000  .1000E-03  2.4000  .0000E+00   .0000     .0000
  .2120    15.00   .1000E+11  .0000  .0000E+00   .0000  .4400E-02  1.0300  .0000E+00   .0000     .0000
  .3080      .00   .6100E-04  .0000  .0000E+00   .0000  .7400E-04  2.2700  .0000E+00   .0000     .0000
  .3080    80.00   .6100E-04  .0000  .0000E+00   .0000  .5400E+00   .2400  .0000E+00   .0000     .0000
          1
```

INITIAL CURRENT= 14000.00   INIT. PROT. R.=   .0550   GAMMA   .00   R. SWITCH=3000000.00   COIL IND.   .0180

INIT. VELOCITY= 7294.46   UNIT CELL AREA = .188900   INITIAL TEMPERATURE = 4.5000

ALPHA = .00500   INIT. X VELOCITY= 515.7963   EPSILON= .78000   INIT. Y VELOCITY= 6442.2940

X COIL DIMENSION= 8.00   Y COIL DIMENSION= 1.16   Z COIL DIMENSION= 172.30

COORDINATES OF SOURCE X= 1.00   Y= .00   Z = 86.20
BREAKER DELAY TIME = .40   INITIAL MAGNETIC FIELD= 117.600KG

time	current	coil resistance	delta volume	ext. voltage	int. energy	int. voltage	theta	isqdt
0.001	13999.89	1.43E-04	2.54E+01	0	27.95	2	7.19	0.2
0.002	13999.69	2.59E-04	2.05E+01	0	50.71	3.62	10.47	0.4
0.003	13999.33	4.54E-04	3.42E+01	0	88.9	6.35	14.76	0.6
0.004	13998.76	7.34E-04	4.79E+01	0	143.91	10.28	23.82	0.8
0.005	13997.9	1.11E-03	6.15E+01	0	216.69	15.48	31.62	1
0.006	13996.68	1.57E-03	7.52E+01	0	307.79	21.99	36.79	1.2
0.007	13995.05	2.10E-03	8.19E+01	0	410.86	29.35	40.7	1.4
0.008	13992.99	2.66E-03	8.22E+01	0	520.18	37.17	44.04	1.6
0.009	13990.44	3.28E-03	8.71E+01	0	642.03	45.88	47.19	1.8

Superconducting Magnet Program

Design Input necessary for Protection Stainless Steel Heater Analysis

Integrated Stainless Steel Specific Heat Versus Peak Temperature

Temperature Adiabatic(K)	Energy/unit volume joules/cubic centimeter
100	80
200	316
300	642
400	1034
500	1494
Kapton Failure 770K	2700

Typical Resistivity (Stainless Steel)	50 micro-ohm-cm
RRR	1.5
Typical Time constants (1/e)	
Heater pulse	30 – 100 milliseconds
Typical detection plus thermal	
Diffusion time at 70% short Sample	~40 milliseconds
(typically the peak MIIT's value)	
Typical Heater Power supply	450v
Parameters (x2 if stacked)	2 to 20 millifarad

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Superconducting Magnet Program

Summary of Typical Process
Protection Heater Design

Obtain MIITs curve for magnet   Calculate from "Quench" code or Measure

Calculate minimum coil volume(conductor length)   I (operate), L (millihenries)

Design heater area greater than necessary Heater area calculated
to switch minimum coil volume(conductor length)

Residual Resistance Ratio (conductor)   Most effective 10 - 20*

Heater design resistances calculated   ohms to few 10's of ohms

Temperature (heater) targets   150K to 200K

Wattage (heater) at the surface $\geq 20 w/cm^2$ for LHe & $\geq 40 w/cm^2$ for Super-fluid He

Time (heater) constants   30 millisec. to ≤ 100 millisec.

*New Knob discovered by serendipity

An efficient heater should: **especially pertinent to longer magnets**

Include an active length (non-cu plated) ≥ 1 cable transposition length

Minimum heater thickness (ss)   13 micron preferred, but 25 micron is normal

Min. thickness Kapton under layer and/or 25 microns (≥ 3 kV checked)
Alumna filled Kapton (x2 thermal conduct.)   25   "   "   thermal diffusion time ~20-25ms

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Superconducting Magnet Program

Training Summary

Olde Method

---Works---

> Provided Structure is able to preload the windings in all directions, such that the coil can not move under any Lorentz load permutation.

Newer Strategy

--Works under careful control--

> Do not bond winding to any surface that is possible to be in shear or non contact with I.e. not surfaces that become unloaded like $\text{Cos}\theta$ winding poles, solenoid spool

> Control integration of the Lorentz forces to limit winding deflections (a field quality issue) I.e. load enough to remove fluff and insure support contact (springs?)

> Higher the metal packing fraction the lower the deflection per given load. (higher ampere-turn) This results in a higher modulus and lower voltages

> Avoid magnet designs with parallel surfaces under load in contact with winding

Superconducting Magnet Program

Protection Heater Mode

- The Heater design is per unit length

  provided the heater is segmented properly

- Therefore heaters can be effective on "Long or Short" magnets

- The length limit using this protection mode is thermal mechanical

  limited by stresses caused by differences in coil's temperature and the support structure

  Later designs attempted <100K

- Overall "J's" in the range of 2000 amperes/mm^2 appear possible at this time although results for windings in the 1000 amperes/mm^2 range are available.